Electrical model of the Alfvén eigenmode exciter on JET

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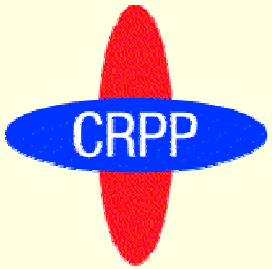
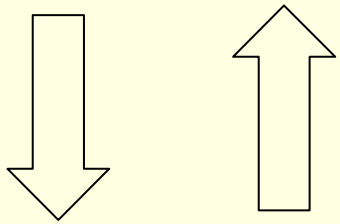
SPS Annual Meeting 2008

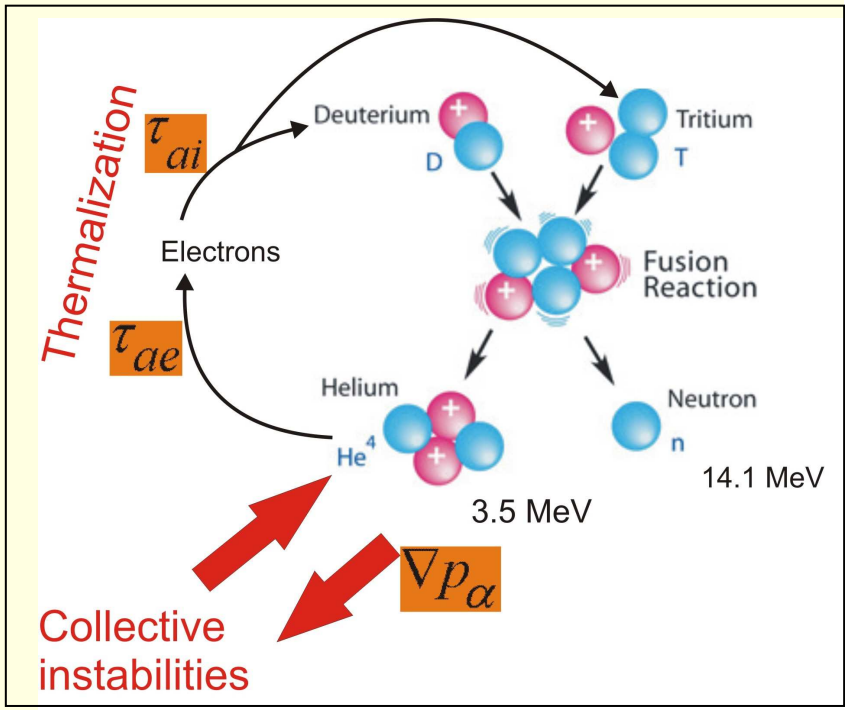


Self-heating in fusion plasmas

- Energetic particle / α particle transport
- Redistribution and losses



- Collective instabilities
  - Alfvén modes
  - Energetic particle modes



- Experiments: energetic particles do drive unstable Alfvén modes

Alfvén eigenmode stability

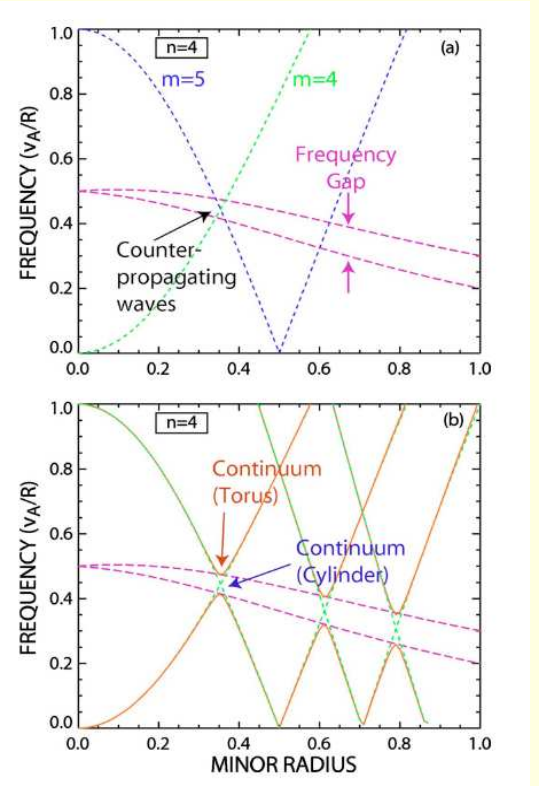
- AEs: Normal modes of background plasma
- "Straight" tokamak: SAW continuous spectrum

$$\omega^2 = \omega_A^2(r) = k_{\parallel}^2(r)\, v_A^2(r) = \frac{v_A^2(r)}{R^2}\left(n + \frac{m}{q(r)}\right)^2 \qquad v_A = \frac{B_0}{\sqrt{\mu_0 \sum n_i m_i}}$$

- Radially extended modes suffer rapid dispersion
- Tokamak: periodic mirror machine
- Poloidal harmonics (n,m) and (n,m+p) interfere to form standing waves: *Gap modes*
- Gap modes avoid heavy continuum damping
  - ↳ Prone to destabilization by energetic particles

Mode stability $\gamma_{damp} = \gamma_{backgr} + \gamma_{EP}$

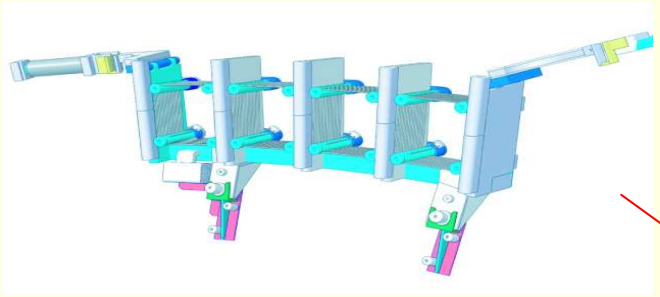
Measurement technique: excite antenna-driven stable modes and sweep across a mode resonance to measure its quality factor = damping rate

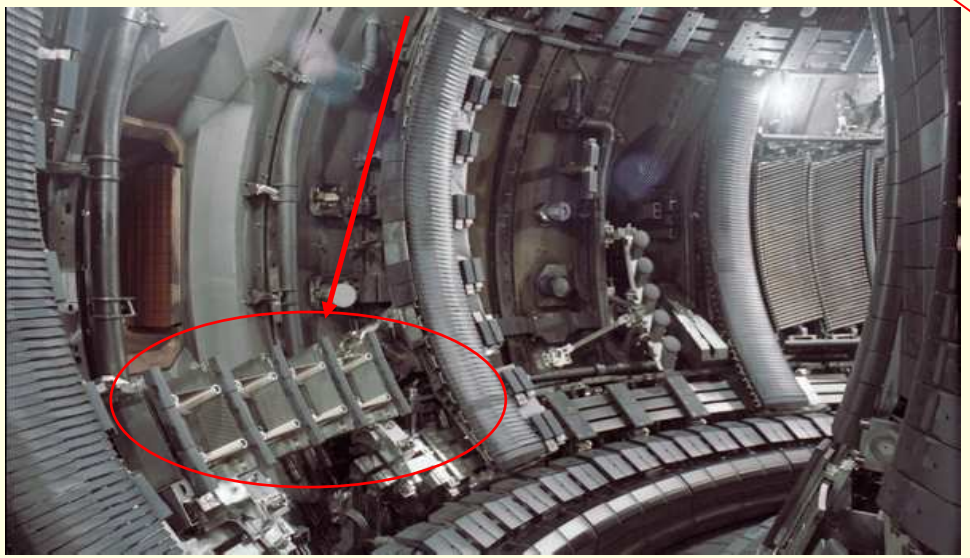


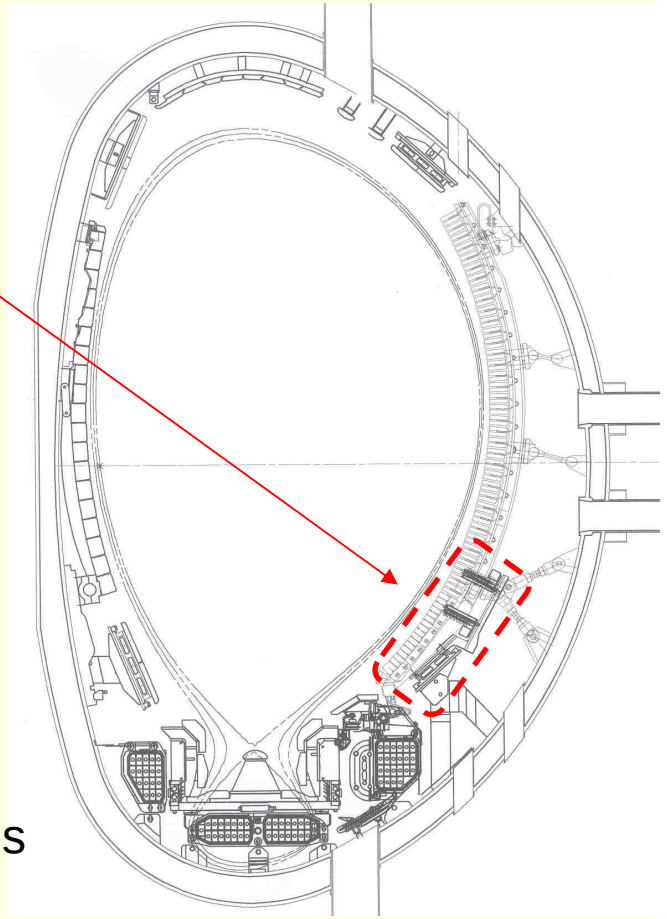
(From: *Heidbrink, 2008*)

- So far: mostly experimental data for low n modes (n=0,1,2) (saddle coils experiments on JET)
- However, predictions for ITER: most unstable modes are intermediate and high n (~5-17)

TAE antennas (high n modes)







- 4 antennas (single octant) in operation in 2007 campaigns
- 8 antennas (2 groups at toroidally opposite positions) will be put in operation in 2008 campaigns

Electrical modeling and matching

Critical parameter for damping measurement: clear signal at sensors

Antenna geometry: Effective area <1 m^2 (saddle coils: 75 m^2)

High n modes have low amplitude at the plasma edge

Antenna impedance results in high-impedance loading at the amplifier output (low current)

Weak perturbations ($\delta B \sim 10^{-4}$ to 10^{-5}G at the LCFS)

↳problem for clear detection of mode resonance on Mirnov coils

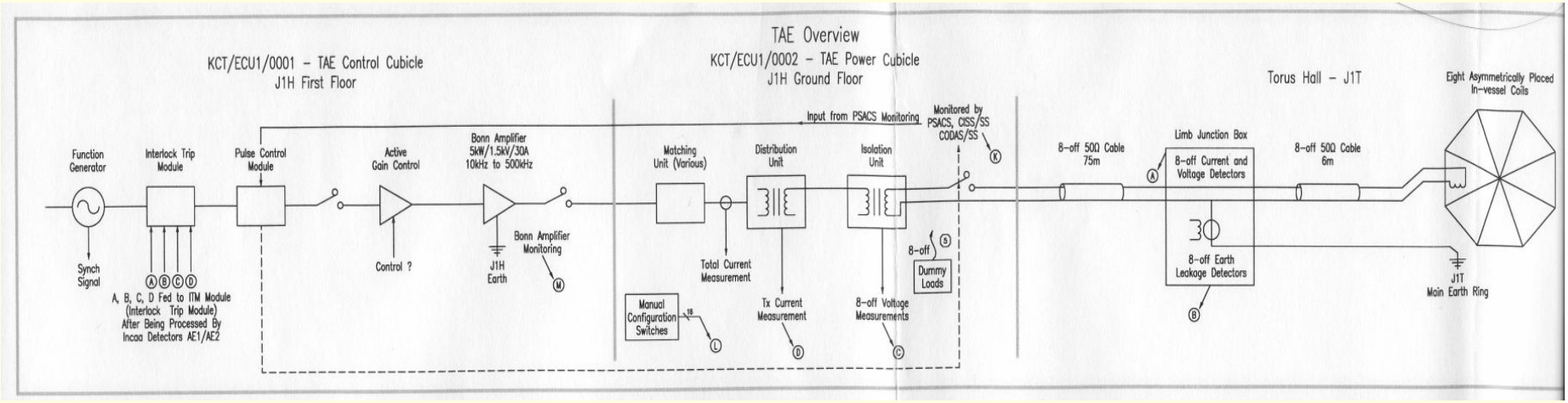
- Better coupling to the plasma through higher antenna current
- Envisaged solution: matching
  - Find appropriate impedance-transformation circuit(s) to maximize the transmission of power from the source to the load (antennas), compatible with operational/engineering constraints

Constraints

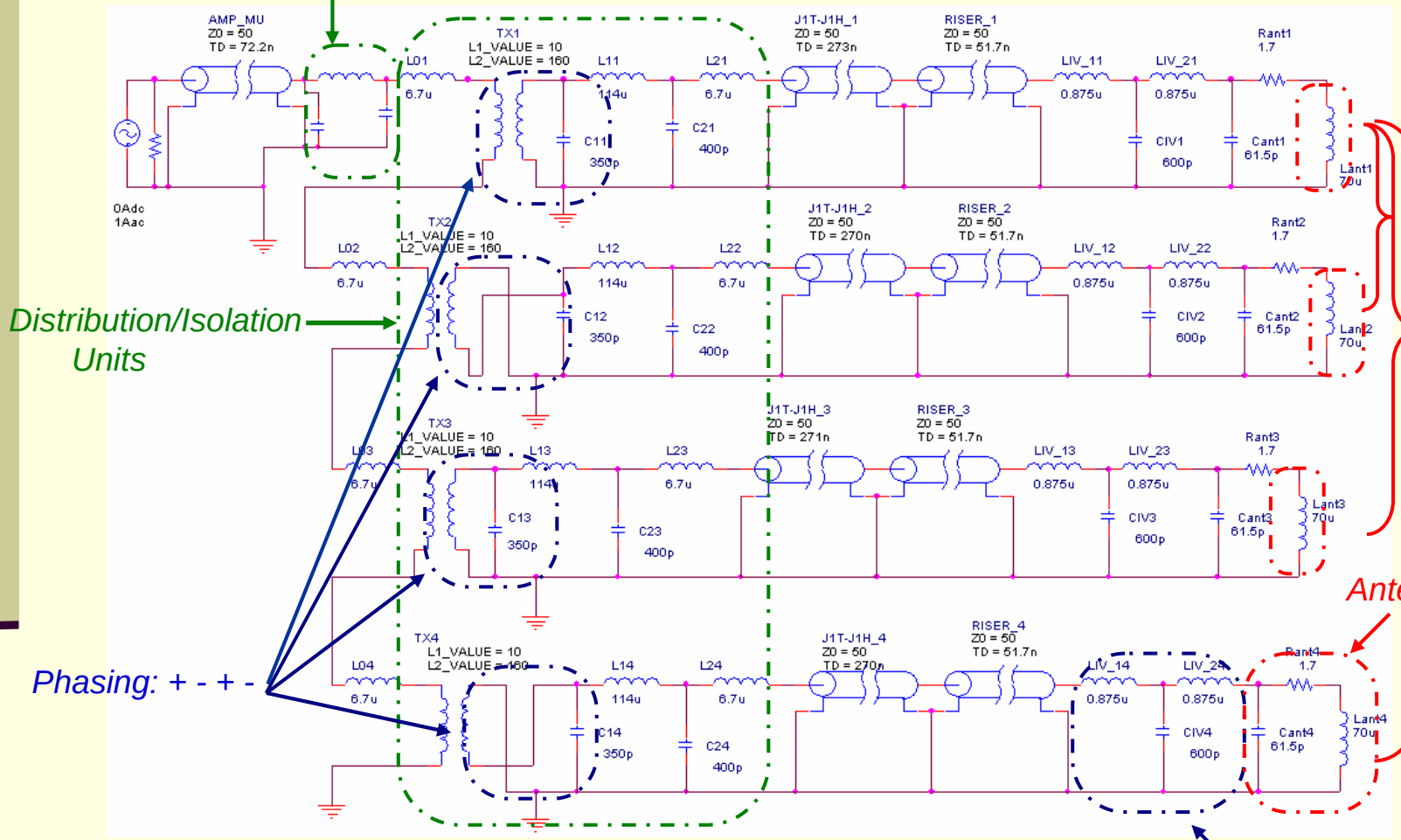
- Amplifier limits: 700 V, 15 A (peak)
- Voltage limit at feedthroughs: 600 V
- Matching circuits at large electrical distance from the antennas
- Broadband operation (20 – 500 kHz)
  - Matching design for narrower bands, for various configurations

Layout of AE exciter

- 5 kW broadband power amplifier
- Matching circuit
- Power splitter (distribution unit)
- Isolation unit
- Coaxial cables (of total length ~106 m)
- V/I measurements at 3 points along the main transmission line
- Nearest point to antennas: “Link-box” (close to transformer limbs)



Model for 4 antennas (in the same octant)

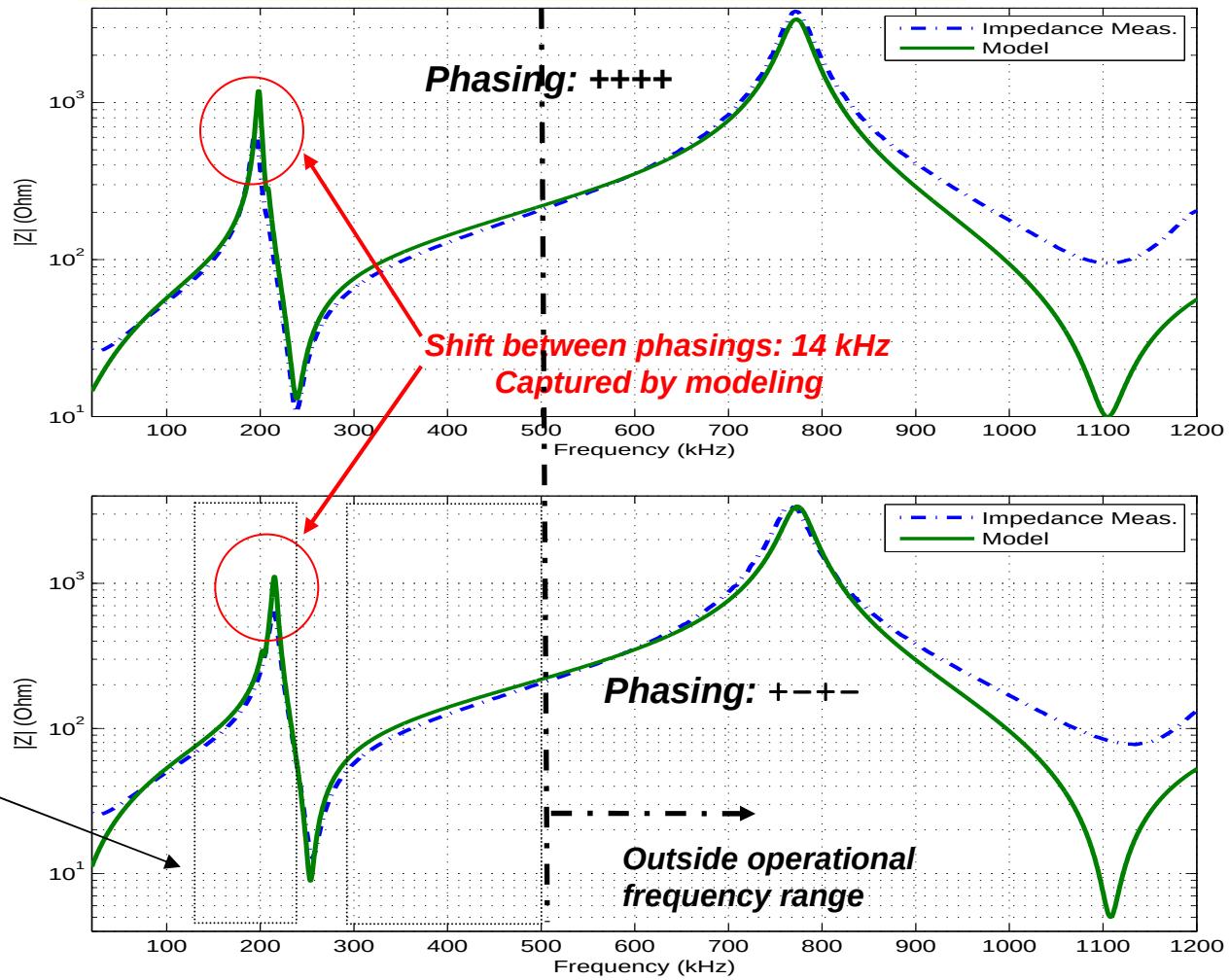


Comparison: model and network analyzer measurements

Impedance at distribution unit input

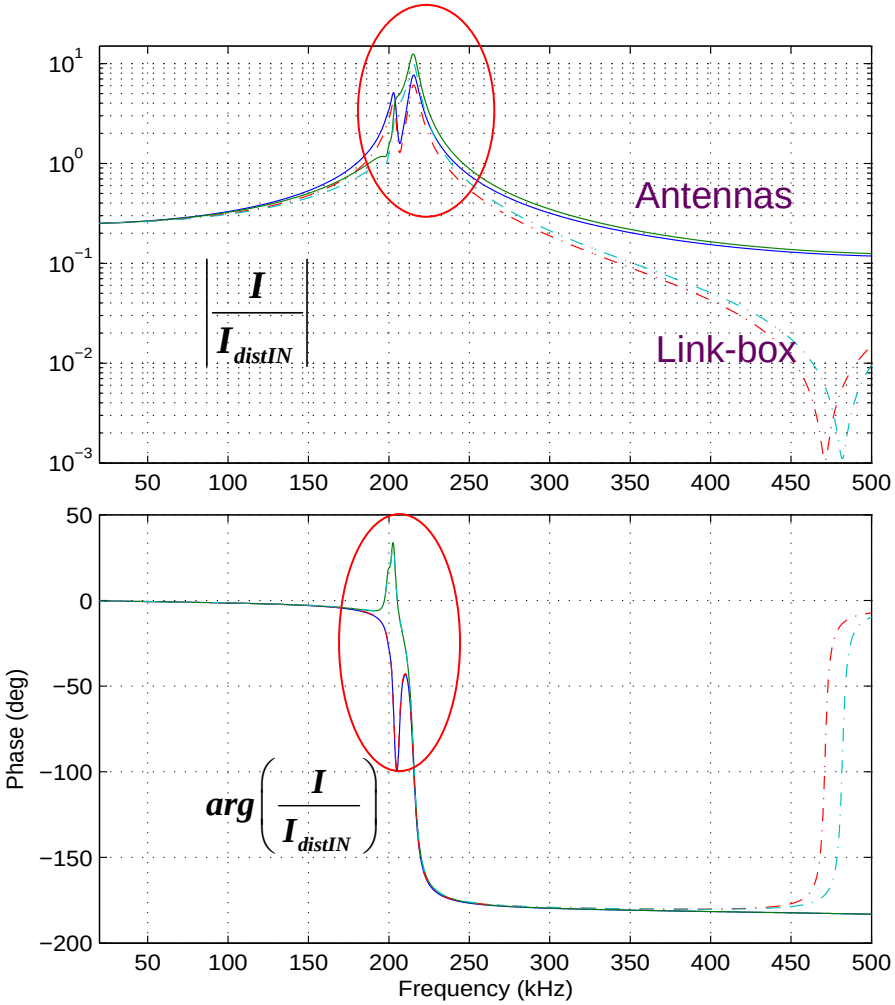
- ✓Very good agreement between model and measureme

Shaded regions: High impedance - low antenna current



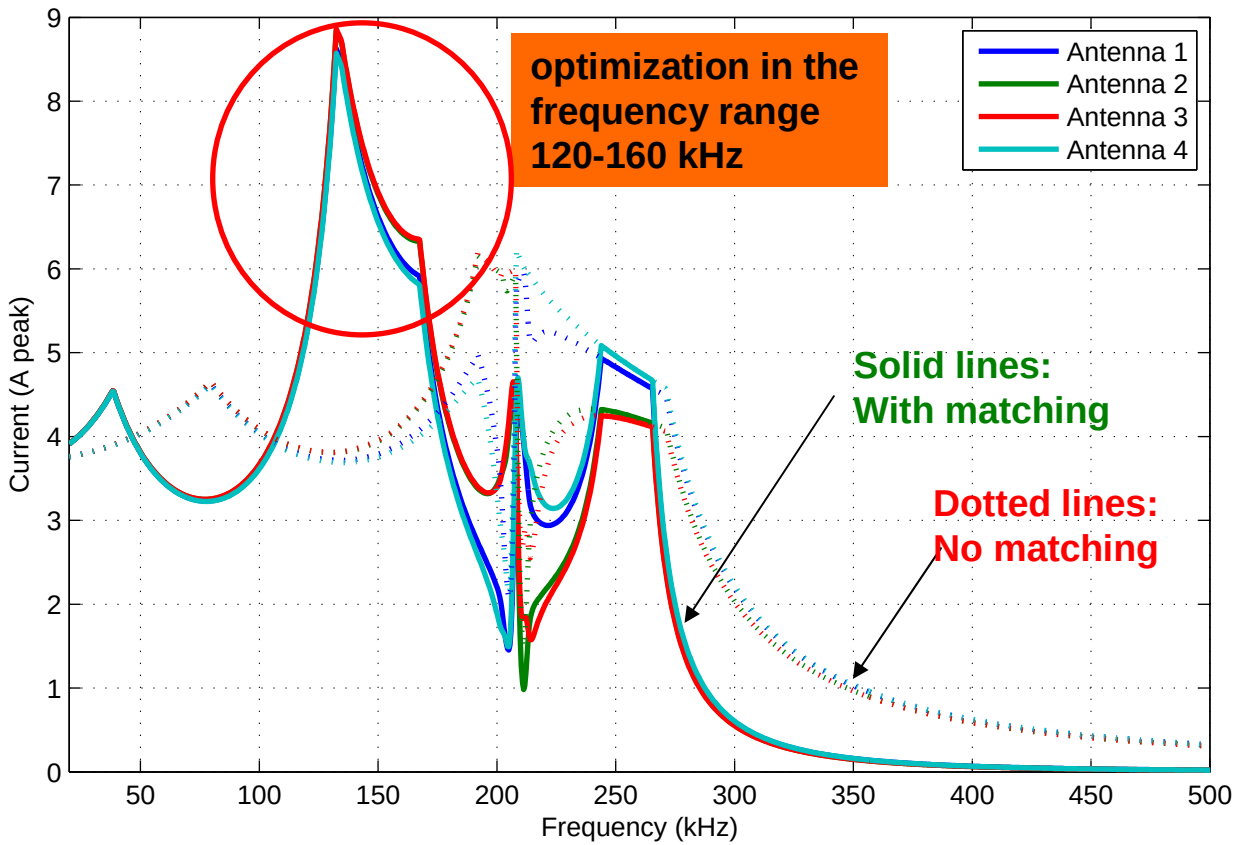
Effects of inductive coupling between antennas

- Antennas self-inductance: ~ 70 μH
- Mutual inductance for adjacent antennas: ~ 5 μH
- Inductive coupling between closely-spaced antennas: perturbation of system transfer functions across a band of a width 40 kHz around 200 kHz
  - Antenna currents do not preserve the nominal current phasing imposed at distribution unit → problem in definition of n
  - Different antennas have different current and voltages

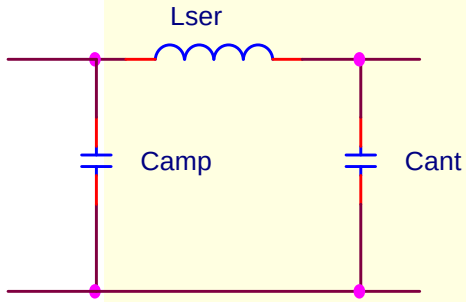


Example of matching (4 antennas)

Maximum currents at the antennas



Matching circuit



Lser = 86.4 μH

Camp = 2.93 nF

Cant = 23.2 nF

Conclusions

- ✓ Model in *very good agreement* with network analyzer impedance measurements
- ✓ Effects of the inductive coupling between the antennas quantified
- ✓ Matching investigation yielded circuits that are expected to *increase antenna current by a factor of 1.5-2* inside their appropriate matching bandwidth: remains to be tested in practice

Electrical analysis is expected to contribute to the full exploitation of the diagnostic system possibilities